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APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

TASK ORDER N-36 REPORT ON

CONCEPTUAL NAVIGATION SYSTEM

Prepared under Contract No. NAS8-11096 by

Doyle Thomas

NORTHROP SPACE LABORATORIES
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Huntsville, Alabama

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PREFACE

This report was prepared by the Northrop Space Laboratories, Huntsville Department, for the George C. Marshall Space Flight Center under authorization of Task Order N-36, Contract NAS8-11096.

The NASA Technical Liaison Representative was Mr. John Harden of the MSFC Astrionics Laboratory (ASTR-AN).

The work completed a seven man-week effort beginning on 1 July 1964 and ending 1 September 1964.

The data presented herein is intended as a conceptual navigation system to be useful for the Lunar Roving Vehicle.

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SUMMARY

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A primary function of a navigation system is that of position determination. This function has been discussed in earlier reports (References 1 and 2). The two methods of position determination that were studied in detail were (1) position determination utilizing orbital parameters of the CSM, and (2) position determination utilizing celestial bodies as references. Of the two methods studied, the latter was concluded to offer the most accuracy. Position determination, via satellite, while potentially a very accurate technique, suffers from orbital parameters which must be taken "as is". To achieve high accuracy utilizing the position of the satellite as a base requires an optimization of the orbit. It is not reasonable to assume that a satellite would be placed in lunar orbit primarily as a navigation aid.

Position determination by celestial navigation offers high accuracy by extending the observations to three or more bodies. Useful position information may be obtained, however, from the observation of a single celestial body (Reference 3).

The navigation system proposed herein is based on the use of a celestial body tracker mounted on a stable platform as the primary method of position determination. A back up dead reckoning system is provided for redundancy and to aid in driver control.

Author

1.0 INTRODUCTION

This report is a summary of the study effort during Task Order N-36. The Scope of Work was to develop a conceptual design for a navigation system for a Lunar Mobile Laboratory (MOLAB) in support of ALSS.

Included in the first portion of this report is a discussion of the general philosophy to be followed for enroute navigation methods. The proposed position determination method is then described and reasons stated for selection of the proposed system. The principal components of the system which are required for implementation are then described.

2.0 GENERAL PHILOSOPHY

2.1 NAVIGATION AIDS

The philosophy of the proposed MOLAB navigation scheme is to provide a system which combines the general functions of navigation, i.e., position determination, dead reckoning, etc., with the particular requirements of the vehicle driver, specifically in regard to pilotage. Latest evidence[1] on the possible nature of the various travel routes indicates that obstacle avoidance, or piloting in the localized area of the MOLAB, will demand a considerable portion of the driver's time. Enroute navigation from one point of scientific interest to the next must be accomplished by quick and ready reference to simple driver aids. One navigation aid would be a Heading Error Display. Such a display should show true heading of the MOLAB in addition to the correction necessary (error signal) to bring the MOLAB to the vicinity of the designated interest point.

A second driver navigation aid that is recommended is a vehicle position plotter. This plotter could be panel mounted, or else remote, to be held by the copilot. The best available lunar map would be inserted in the plotter and the starting point made to coincide with the latitude and longitude determined by the celestial position fix. Subsequent vehicle motion would be resolved into components to drive the plotter. This provides then a record of the path taken by the MOLAB across the surface.

The method of position determination depends on the use of a celestial body tracker. The recommended body to track is the earth, or the sun during periods of time when the sun appears adjacent to the

1. Photographs of Moon's surface by Ranger VII.

Earth. By continuous tracking of the Earth as the vehicle is in motion, a continuous position readout is available. When desired, or when the computed position of the vehicle differs markedly from the position determined by the Earth Tracker, the plotter is reset and the process starts again.

This arrangement provides for driver control and useable position information over the enroute paths while providing the potentiality of higher accuracy position readouts whenever desired. Redundancy is provided in that the two types of position determination, i. e., celestially and by dead reckoning, provide a comparison which may be used to quickly spot a faulty unit.

2.2 FUNCTIONS BY EQUIPMENT TYPE

The various navigation functions, which are inherent in a self contained system, are listed with a description of which equipment satisfies the requirement.

a. Position Determination

A combination of the Earth/Sun Tracker and the Vehicle Attitude and Heading Reference Package provide a measurement of the angles required to compute present position. The Earth/Sun Tracker provides an altitude and azimuth angle to the Earth or the Sun. The Vehicle Attitude and Heading Reference Package provide true heading in addition to a local level platform for the tracker. When combined properly, these angles will provide true azimuth and true elevation to the observed body. The principle of position finding is that of a one body fix.

b. Conversion

The navigation computer which is a special purpose digital computer processes the azimuth and elevation angles from the Earth Tracker and provides the latitude and longitude coordinates of the observation point.

c. Comparison

The derived coordinates may be compared on a lunar map to find the heading and straight line distance to the next point of interest. In an automatic mode the desired coordinates are inserted into the computer. Straight forward calculation yields the bearing and distance outputs. During travel, updated latitude and longitude data is used to continually display the required heading information to the point of interest.

d. Computation

The computed updated position of the MOLAB is obtained by resolving the distance traveled into three mutually orthogonal axis to represent distance traveled over the surface and in altitude.

2.3 MODES OF OPERATION

The following modes of operation are suggested for the conceptual system.

a. Celestial, Single Body
b. Celestial, Multiple Body
c. Dead Reckoning
d. Piloting

3.0 PROPOSED SYSTEM

3.1 SELECTION OF THE CELESTIAL BODY

The proposed method of position fixing is based on the principal of position determination by celestial observation of a single body. If the azimuth angle to the body can be measured accurately then the location of the observer can be determined. The principal reason for utilizing a single body is to allow vehicle freedom while maintaining the celestial body in the line of sight. Two stars, for example, located ninety degrees apart in the lunar sky requires a cone of visibility above the MOLAB greater than that required for a single body, if the two stars are to be observed over an extended period of time. Intermittent observation of two or more stars by an automatic star tracker has associated with it the acquisition problem and the large catalog of star combinations which must be available to allow control of the MOLAB from a remote position during any portion of the month. By utilizing one body the tracker may be left on continuously while the MOLAB is in motion.

In answer to the question "which celestial body should be tracked?"; it is recommended that the Earth be used as a primary reference body. The Earth has two distinct advantages over other celestial bodies. First, since the spin rate of the moon corresponds with its orbital period about the Earth, then the Earth, as viewed from the lunar surface, will remain fixed in the sky. The geographical position of the mean Earth-Moon intercept becomes a fixed point on the lunar surface. This point may be used in the same manner as the North Pole is used on the Earth.

The mean Earth-Moon intercept point is located at latitude and longitude zero. Due to the physical and optical librations of the Moon, the Earth-Moon intercept point will move through an angle represented by a cone not greater than eight degrees from the mean Earth-Moon intercept line. The motion of this geographical point is known to a high degree of accuracy (Reference 4). The limited motion of the Earth in the sky thus requires a cone of visibility less than that required of other celestial bodies.

The required visibility cone is equal to the sum of the maximums of the vehicle attitude and the declination of the Earth from the observation point. For a maximum vehicle attitude of thirty degrees and a maximum declination angle of forty-eight degrees, the required cone of visibility for continuous tracking at any time of the month is equal to 156 degrees.

Secondly, the MOLAB must be in constant communication with the Earth, hence angles obtained from pointing the directional antenna are available for use. Tracking the Earth then provides the possibility of a dual function which satisfies the navigation system as well as the communication system.

The area of exploration of the first MOLAB mission has been designated (Reference 5) as 40 degrees W and 4 degrees N. This is shown on Figure 1 "Geometric Model of Position Fixing Using Earth Reference", in relationship to the geographical position of the subearth point on the moon. From the designated area of exploration the Earth will be at an altitude angle of 50 degrees. For the radius of the Moon of 1738 km, this establishes a circle of position of approximately 1000 km diameter. With an additional measurement of the azimuth angle, the position is determined.

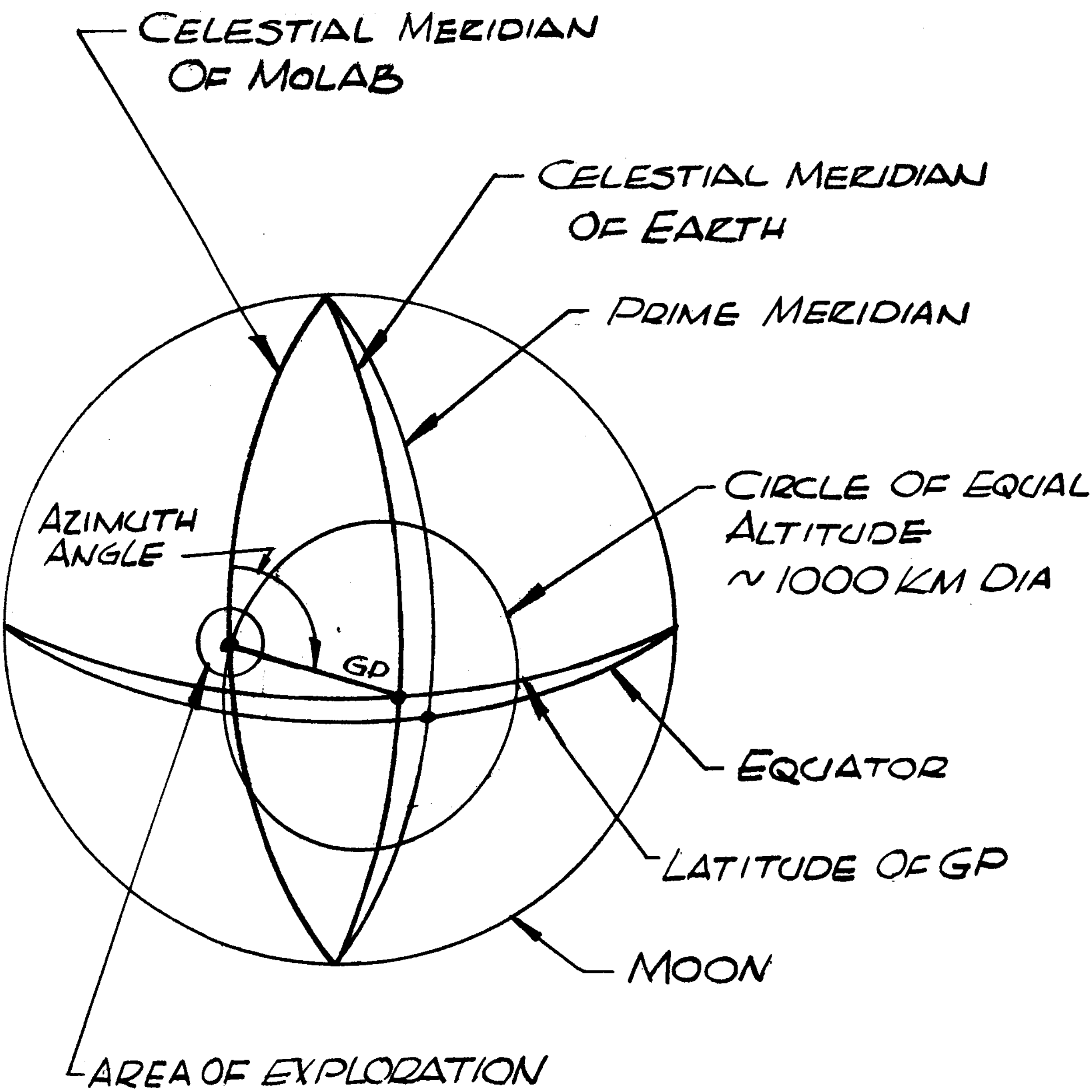

FIGURE 1. GEOMETRIC MODEL OF POSITION FIXING USING EARTH REFERENCE

The design of a system utilizing the principle discussed above is predicted on the following:

(1) A method of measuring line of sight angles to the Earth from a horizontal plane unaffected by the dynamics of the MOLAB.

(2) An accurate angle positioning and measuring system.

The requirement for a horizontal plane from which the angles may be measured requires a stable platform. On the platform a horizon system of coordinates is established. This system is a right handed coordinate system consisting of the directions to (a) the zenith, (b) the north pole, and (c) the East. This requirement is most easily realized by a Schuler tuned stabilized platform. The platform is to be made large enough to handle a separately gimbaled azimuth-elevation planet tracker. The planet tracker affords the means of accurately measuring the angles and tracking the Earth.

Earth Tracking

Both the navigation and communication systems on the MOLAB may require Earth tracking. There are two orders of magnitude difference, however, between the accuracy required for communication and that required for navigation purposes. The communication function is satisfied by maintaining the Earth within the half power points of the antenna beam width. This is estimated to be on the order of five to eight degrees. For useful navigation, however, the directions to the Earth from the platform should be determined within .1 degrees or better. Furthermore, the inertia of the antenna will be several times larger than that of a planet tracker. Because of these reasons, it is recommended that the antenna be slaved to the planet tracker. This is opposed to the idea of having the antenna track the DSIF stations on Earth. The additional equipment required for tracking a DSIF station by either interferonometer techniques or conical scanning methods can be traded for the planet tracker and associated electronics, in order to serve both needs. The antenna can be suitably mounted to the structure through a two gimbal azimuth-elevation mount. Thus, the pointing direction of the antenna can be achieved by means of transformation of coordinates from the planet tracker, provided the two are mounted on the same rigid frames which are a part of the vehicle structure. The same philosophy could also be applied to the T. V. camera. Thus, the servo platforms may be kept to a minimum, reducing the overall power requirements. These ideas are shown pictionally in Figure 2.

3.2 PRINCIPAL COMPONENTS

The principal components of the navigation concept are:

(1) A central MOLAB attitude and heading reference package.

(2) An Earth/Sun Tracker system capable of tracking either the Earth or the Sun.

(3) Dead Reckoning Sensors to yield distance traveled along the path.

(4) A navigation computer to compute position either celestially or by Dead Reckoning techniques.

(5) An integrated display panel to provide mode control and navigation displays.

The simplified block diagram, Figure 3, shows the relationship of these components to each other.

The primary mode of operation for the vehicle will be navigation in a dead reckoning mode. In this mode the distance traveled is resolved into three mutually orthogonal components. The components are obtained by the use of the Attitude and Heading Reference Package which is maintained level and aligned to true north by the action of the gyro torque computer. The latitude and longitude components are plotted on a vehicle position plotter. This plot will provide a visual picture of the path taken by the MOLAB. Maps of the exploration area are to be prepared and inserted in the vehicle position plotter prior to travel. The initial starting point for the position plot is to be established manually from information displayed on the latitude longitude readouts. An additional aid to the driver is a heading readout which shows true heading of the vehicle as well as error in established heading to arrive at a designated point.

Altitude is displayed on a meter. This is obtained by resolving the distance traveled into up and down components by the use of the pitch angle readout. The meter will be an integrating device to indicate total accumulated vertical distance in relation to the starting

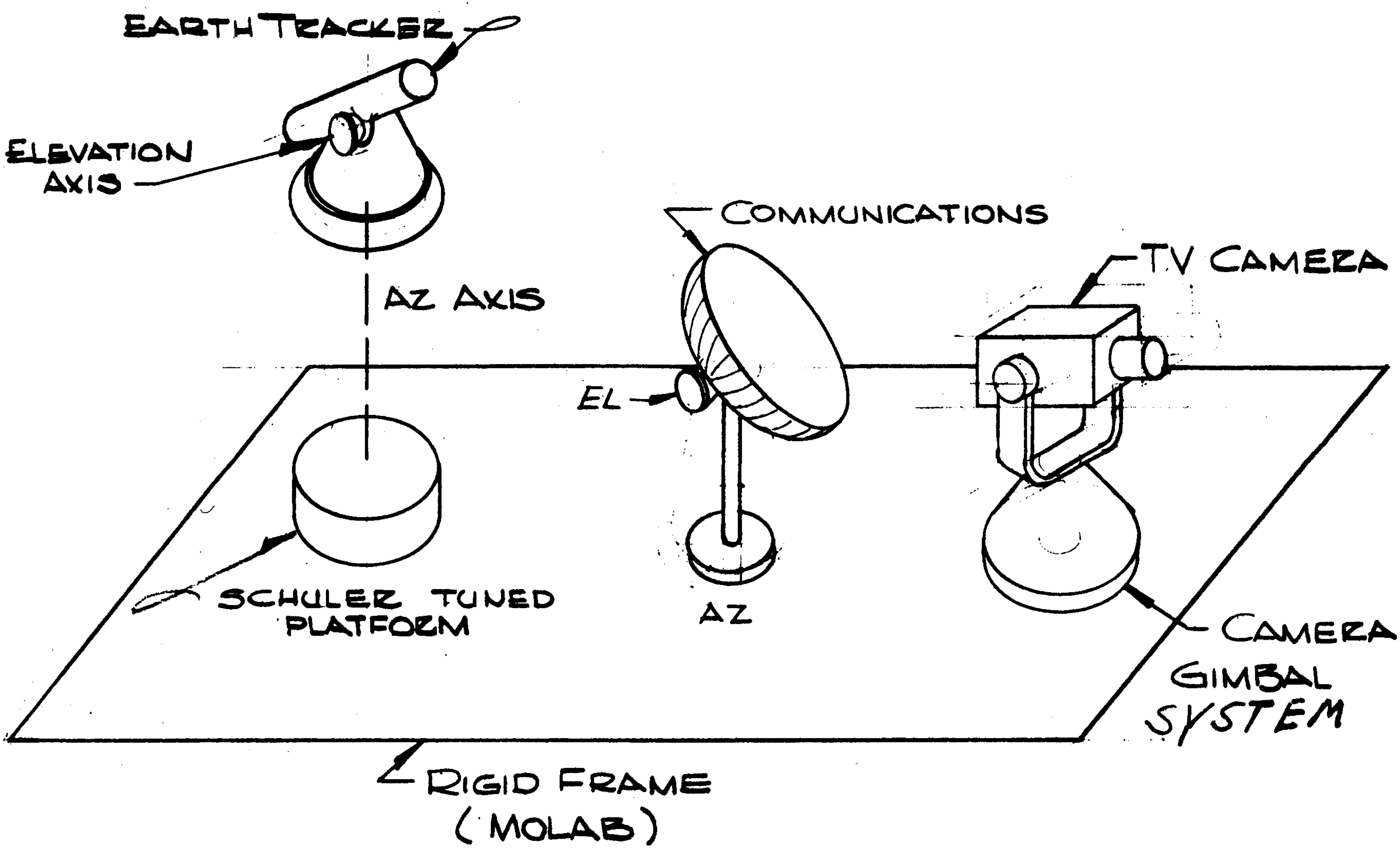

FIGURE 2. SUGGESTED RELATIONSHIP OF OTHER SYSTEMS TO NAVIGATION SYSTEM EARTH TRACKER

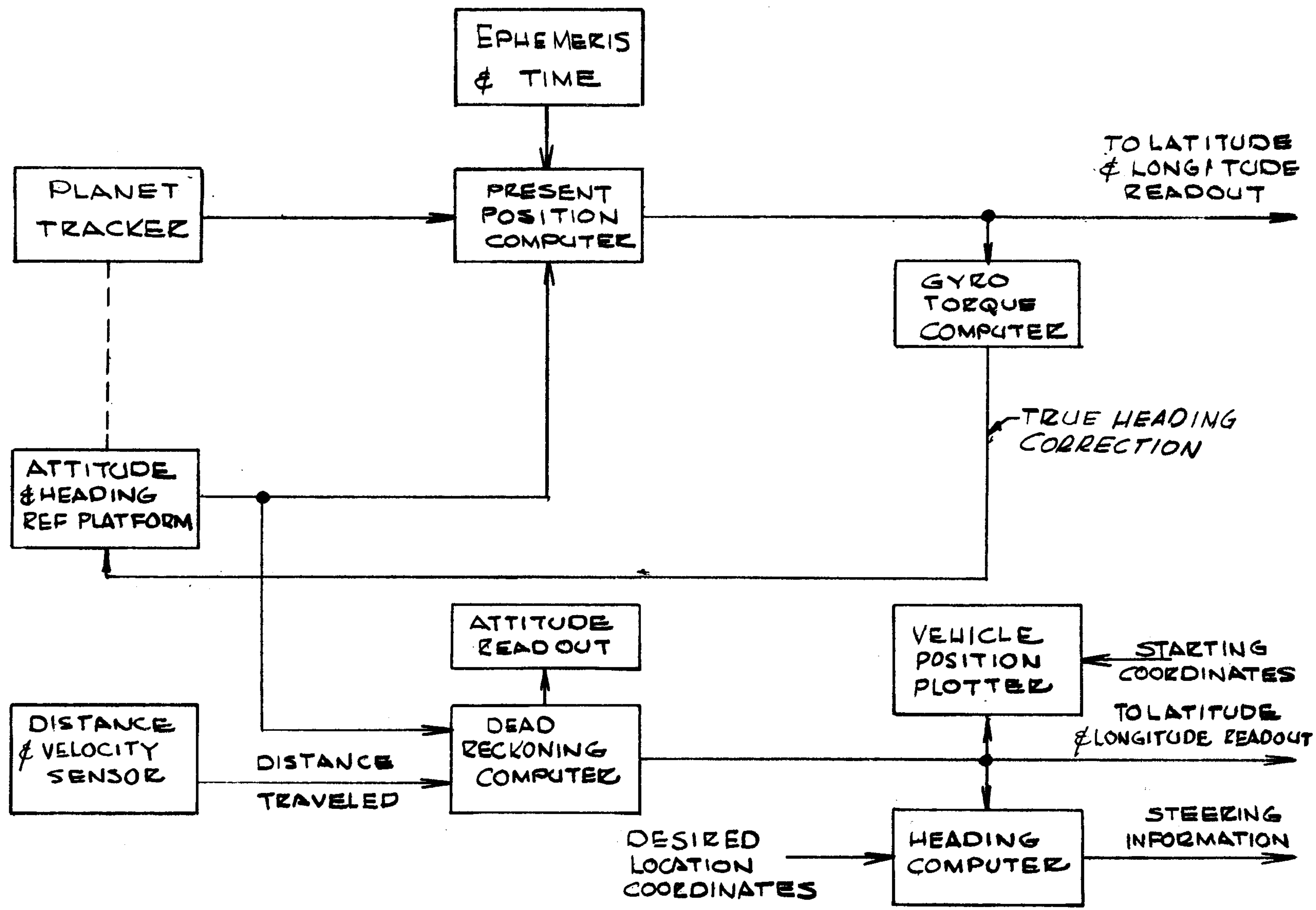

FIGURE 3. SIMPLIFIED BLOCK DIAGRAM

point, or the LEM, which is established as zero.

During the early phase of the mission, the continuous position displayed on the meter can be compared with the latitude and longitude derived by the dead reckoning portion. Also the errors in the dead reckoning portion will increase as a function of distance traveled. Thus when the error becomes excessive the dead reckoning computer is reset, the plotter is realigned to a new starting point and the process starts again.

3.3 ATTITUDE AND HEADING REFERENCE PACKAGE

The Attitude and Heading Reference Package is a centrally located subsystem which performs the following functions:

(a) Provides a local vertical platform as a base for mounting of an Earth/Sun Tracker.

(b) Provides a heading reference which may be aligned in a true north direction.

(c) Provides gimbal readouts which establish the vehicle orientation in relation to the vertical and to true north.

The platform must remain level during motion of the vehicle on the surface. The required motion is as follows:

Azimuth---------------------360^o
Pitch-----------------------$\pm 30^o$
Roll------------------------$\pm 30^o$

Note that item (a) above could be eliminated from this list. The Earth/Sun tracker could utilize the MOLAB frame as a base. By combining the measured angles from the tracker with those from the separately housed attitude readout package, the true azimuth and elevation angle to the body could be obtained. The disadvantage of such an arrangement lies in the distortions in the frame which may exist between the point of mounting of the platform and the point of mounting of the tracking instrument. Because of this reason it was decided that the platform and the tracking instrument should be contained in a single package. For highest accuracy the tracking optics should become an integral part of the stable platform from which attitude measurements are obtained. The selection of the platform to be used on the MOLAB is based on the considerations of accuracy, weight and power requirements, and reliability. Several alternatives are available as choices. These are as follows:

(a) Pendulous platform slaved to vertical gyro with a separate directional gyro for a heading reference.

(b) A gyro-stabilized platform which is initially leveled and established in heading. Such a platform would be run open loop; that is, the torquing functions necessary to maintain the platform vertical would be computed based on knowledge of the required torquing rates.

(c) A gyro-stabilized platform which includes platform leveling and heading functions but with the added feature of Schuler tuning. The Schuler tuning feature would act to maintain the vertical in the presence of accelerations and would not require the additional torquing computer.

Case (a) above, the pendulous platform which is slaved to a vertical gyro for maintaing the platform level, is the method employed in the Kollsman Instrument Corporation Automatic Astro Compass KS-50-06 (MD-1). In such a system the ultimate accuracy is dependent upon the angles of altitude and bearing of the celestial body relative to the horizontal plane. The accuracy of the horizontal plane, in turn, is contingent upon the ability of the vertical gyro to maintain the vertical under dynamic conditions, and the ability of the gyro torque computer to compensate for the various sources of tilt error.

Compensation is necessary for the vertical gyro for pitch and roll error due to the moon's spin rate and due to the Coriolis acceleration. Unless compensated for the effect of moon spin rate will produce tilt errors in the pitch and roll axis as follows:

$$\text{Pitch Error} = \omega_m(\cos\lambda)(\sin\psi)$$

$$\text{Roll Error} = \omega_m(\cos\lambda)(\cos\psi)$$

where

ω_m = moon's rate = .536 degrees per hr.

λ = latitude

ψ = heading measured from north.

These are significant errors and must be compensated for.

An additional error in the pitch channel is caused by the MOLAB moving over the surface of the moon. Since the moon may be considered as a sphere then the MOLAB will tend to pitch forward. This effect produces the same sort of error as the moon's spin rate. The pitch error due to the velocity of the MOLAB is given by

$$\text{Pitch Error} = \frac{\nu}{R}$$

where

ν = velocity of the MOLAB

R = radius of the moon.

For ν = 5 km/hr and R = 1738 km the pitch error becomes .00276 arc minutes per second. An erection time constant on the order of 200 seconds would result in a steady state error of .552 arc minutes.* This is a fairly significant error and it may be desirable to provide compensation. The compensation would be equal to $(H)(\nu/R)$ where H is the angular momentum of the gyro.

An additional error source that is commonly compensated for is the Coriolis error. This error is generated by the motion of the MOLAB on the moon and is given by the relationship

$$\text{Coriolis error} = 2\ \omega_m(\nu)\sin\lambda$$

Due to the sin of the latitude angle and the slow velocity of the MOLAB the compensation for this error source may be neglected.

In addition to the above error sources affecting the vertical other errors associated with the dynamics of the vehicle must be taken into account. Careful selection of components to achieve long time constants for the gyro and pendulum must be made to reduce the effect of acceleration errors generated through vehicle dynamics. Long time constants provide filtering of the vehicle motions. Such long time

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*This analysis is correct for an erection loop which a proportional type servo loop. The use of a second order system as is done in the Schuler tuned case eliminates the velocity error.

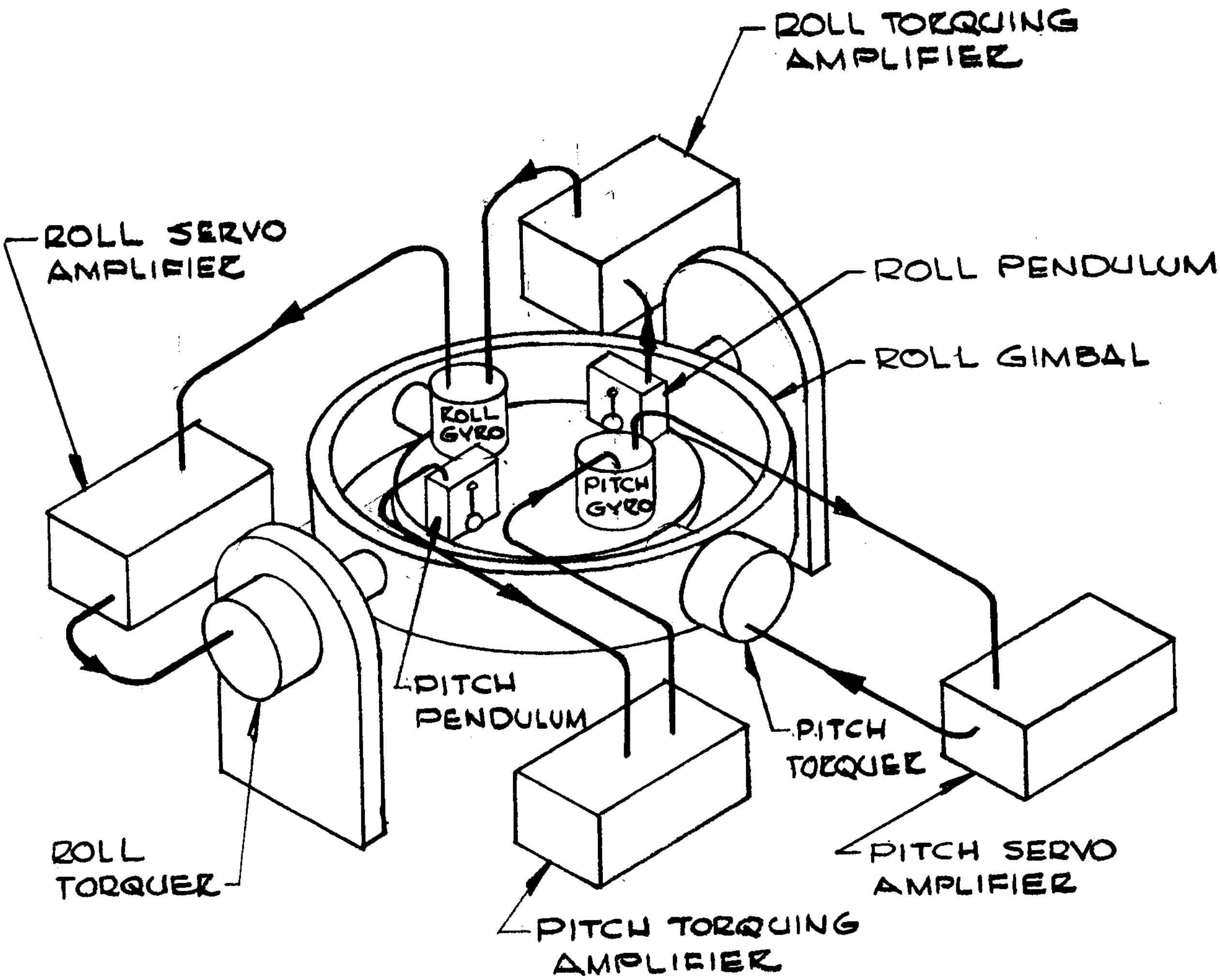

FIGURE 4. GYRO VERTICAL USING SINGLE DEGREE OF FREEDOM GYROS

constants, however, are difficult to obtain. The gyro time constant on the MD-1 astro compass is quoted as less than one minute. This results in significant errors which would prevent the use of such an arrangement for the MOLAB.

Additionally the use of a two degree of freedom gyroscope requires the use of ball bearings at the gimbal supports. Current state-of-the-art gyros are single degree of freedom instruments which employ the rotor suspended in a fluid whose density is equal to that of the spinning rotor. This effectively reduces to reaction torques to zero and results in an order of magnitude improvement in gyro performance.

Case 2: By taking the system discussed in Case 1 above, and incorporating the gyros onto the platform along with the pendulum, greatly improved performance may be attained. This is principally due to the use of single degree of freedom gyros in lieu of the two degrees of freedom vertical gyro. A sketch of the resultant package is shown in Figure 4. In this type of an arrangement the time constant of the vertical gyro servo loop can be adjusted to be long enough to provide filtering of the vehicle dynamics. Thus there remains only the problem of generating the required torque to cancel the errors associated with the moon's spin rate and vehicle velocity.

In order to provide a heading reference a third axis may be incorporated with an additional gyro. Mounted on the platform is also a north seeking gyro. The north seeking gyro provides for alignment of the azimuth axis during the time when the vehicle is at rest. After the north seeking gyro has determined north the platform is aligned and the azimuth gyro is utilized to maintain alignment during periods of vehicle motion.

The components necessary to achieve and implement this type of a platform are as follows:

3	-	S. D. F. Gyros
3	-	Torquers (one per axis)
3	-	Readout devices (one set per axis)
2	-	Vertical sensing elements
1	-	North seeking gyro
1	-	Gyro Torque Computer

Case 3: At very little additional complexity the platform discussed above may be Schuler tuned. This merely requires the elimination of the external torque computer and the use of high quality accelerometers which are used to continually apply erection signals to the platform. By adjustment of the gain of this loop the platform may be Schuler tuned. This would maintain the platform perpendicular to the local vertical. It also reduces the long term errors resulting from certain instrument perfections. The use of accelerometers will allow the possibility of another redundant mode of dead reckoning should this become desirable.

In summary, the requirements for the platform are as follows:

(1) Mounting base for Earth/Sun Tracker.

(2) Three gimbal system.

(3) Accurate gyros, single axis, floated type with minimum drift.

(4) Schuler tuning.

(5) Minimum size and weight.

The recommended platform is an advanced design astro inertial combination typical of the kind employed in advanced weapons systems in use. A sketch of the possible configuration of the platform, with the SUN/EARTH tracker, is shown in Figure 5.

3.4 CELESTIAL BODY TRACKER

Tracking of the Earth from the lunar surface is essentially the same situation as that of tracking the moon from the earth. The solar radiation reflected by the body from the illuminated hemispherical portion of the lunar surface varies from a full circle to a thin illuminated cresent. The problem is that of determining the center of the body. A report (Reference 6) by Roger S. Estey discusses the development of a moon tracker. This work involved a theoretical study and included a laboratory model of a successful moon tracker. The model demonstrated tracking of the center of the moon to an accuracy of 20 arc-seconds from a steady platform. It is assumed that tracking of the earth from a steady platform on the moon could be achieved with similar accuracy. One problem associated with this

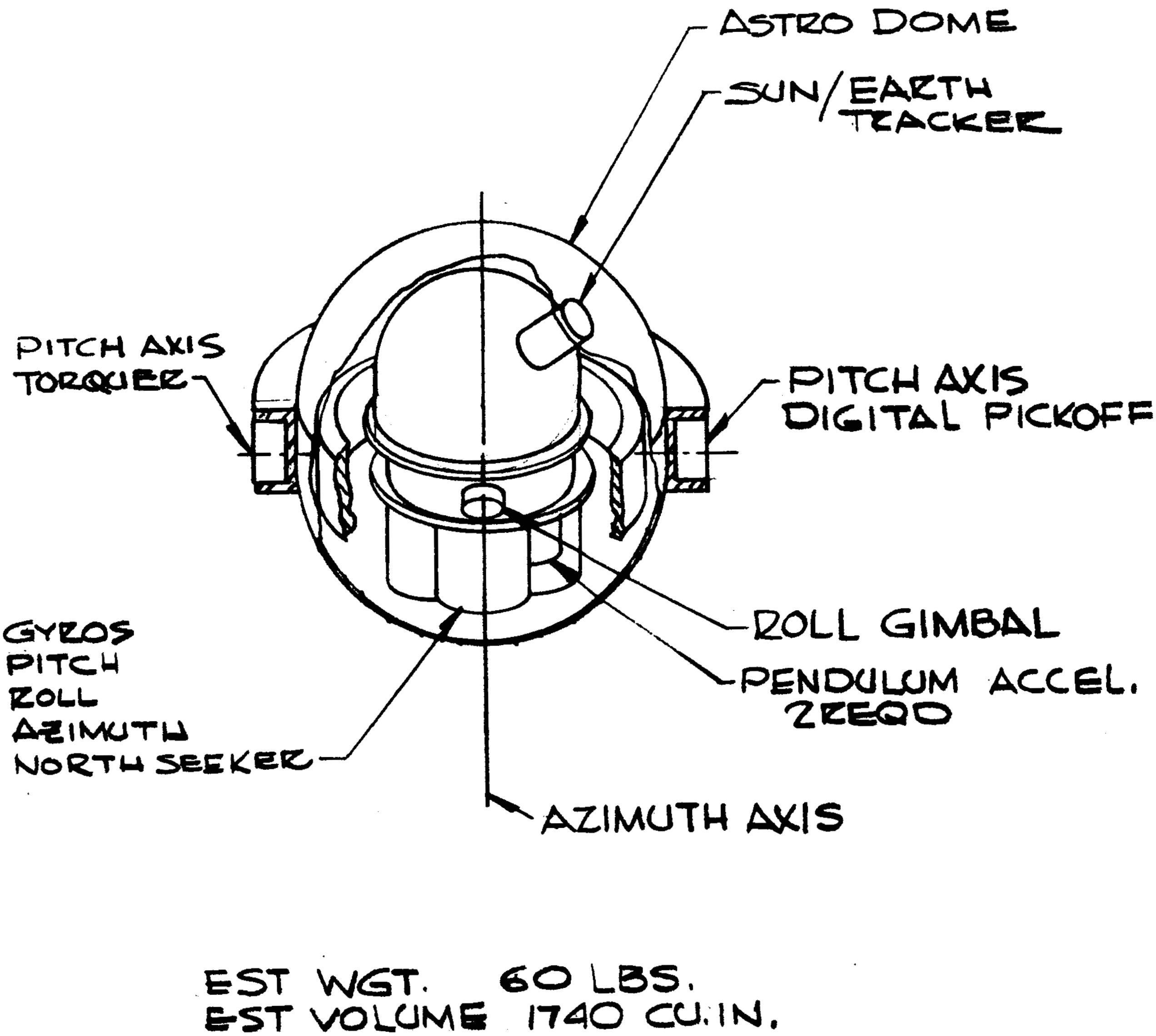

FIGURE 5. CONFIGURATION OF VEHICLE ATTITUDE AND HEADING REFERENCE PLATFORM

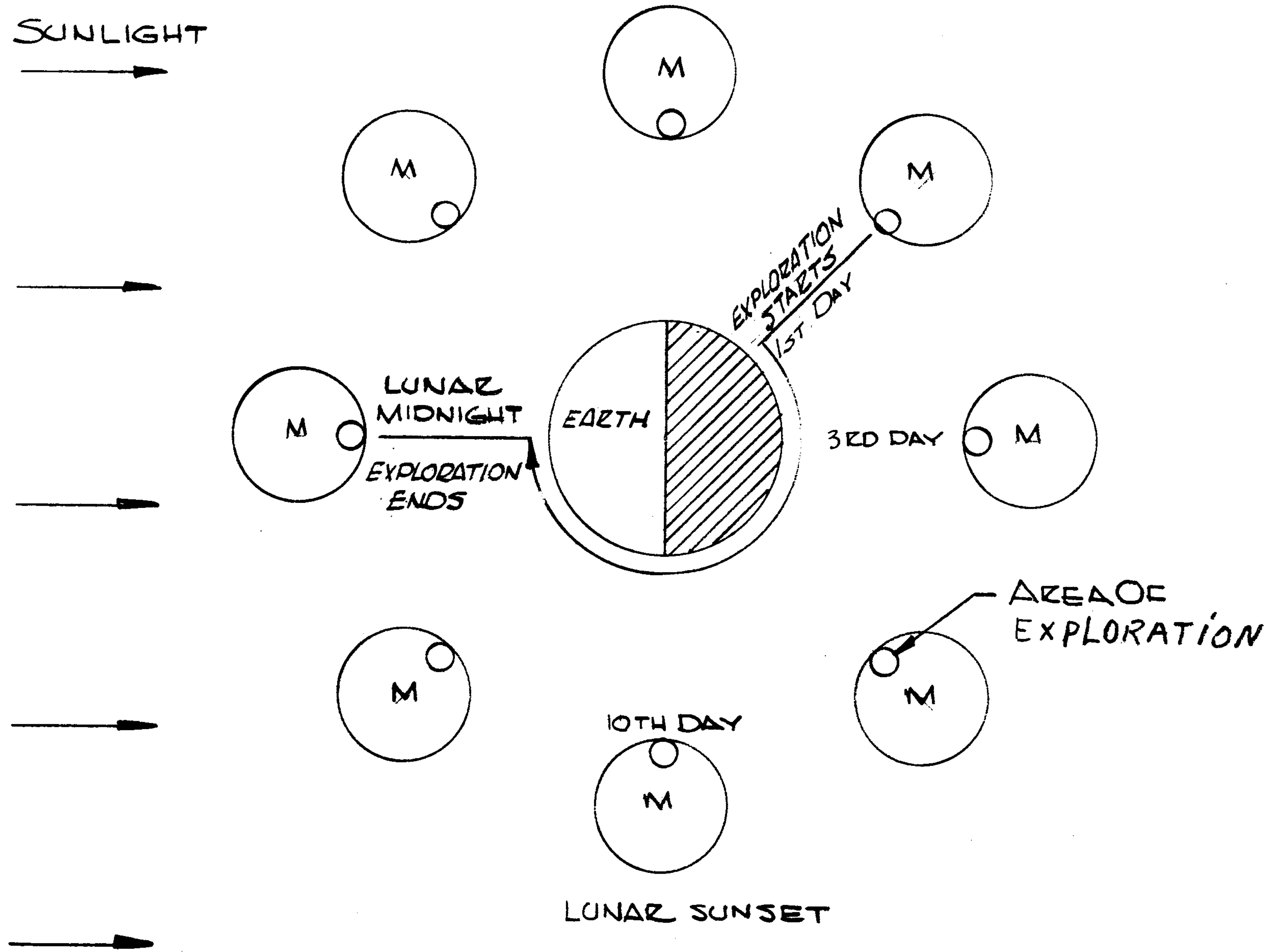

FIGURE 6. PHASE OF MOON IN RELATION TO DAYLIGHT SIDE OF THE EARTH

is the tracking of the earth during the period of the second and third day during new earth periods. This is illustrated in Figure 6. On the third day of exploration at lunar noon, the view of the earth is the view of side away from the sun; hence, no reflected light will be observed. Further information concerning the appearance of the earth from the moon is needed. It is possible that the atmosphere of the earth will cause an airglow ring to be observed during this period, which may be tracked.

An alternate approach would be the use of a star tracker in lieu of Earth as a tracking reference. The same principles might apply, however, in that the communication antenna could still be pointing toward the earth through a coordinate transformation network.

The proposed solution to this problem is the use of optics which may be changed to track either the Earth or the Sun. Since both bodies will subtend approximately the same angle in the sky then an additional filter inserted in the optics should allow tracking of either the Sun or the Earth.

3.5 DEAD RECKONING

The primary purpose of the dead reckoning portion of the navigation system is to provide the vehicle driver with basic navigation aids which will simplify the task of driving the MOLAB. It is anticipated that the lunar maps will be used as continuous references. The dead reckoning equipment utilizes this map in a vehicle position plotter which provides a continuous display of the path taken by the MOLAB. In conjunction with the vehicle position plotter is a heading error display. This gives the operator at a glance his true heading, and provides a steering correction signal to show the correction to be made to bring the vehicle on course to the desired location. With these two bits of information the driver can continuously refer to the vehicle position plotter and the heading error display to see his location in respect to any terrain features he might observe. This then obviates the requirement of transferring computed coordinates onto the map manually.

The principal sources of information for the continuous position display are:

(a) Distance Input
(b) Vehicle Attitude

(c) Heading
(d) Computer
(e) Heading Error Display
(f) Vehicle Position Plotter

These various items are shown in Figure 7, "Block Diagram of Dead Reckoning Equipment". Illustrated on this diagram are the various display outputs which may be used to provide the driver the navigation aids discussed in paragraph 2.1.

4.0 ALTERNATIVES

An attractive alternate to the use of a star tracking instrument or an Earth/Sun Tracker is available by the use of high precession low drift gyros such as ESG's. Two of these two degrees of freedom gyros are mounted onto the platform and initially aligned in two reference directions, such as North and Aries. The ESG's hold the reference directions in space in the same manner as multiple star trackers. Reading of the output angles between the ESG's and the stable platform provides the angles necessary to compute position, as in the case of a celestial two body fix. The drift rate of the ESG's would cause an error to exist after a period of time. Resetting of the gimbal angles could be manually performed by the astronaut, or else optically linked to the transit. This proposed system would allow the platform to be contained lower in the cabin and eliminate the astrodome.

5.0 PHYSICAL CHARACTERISTICS

The estimated weight and power requirements are shown in Table 1.

TABLE 1
CONCEPTUAL NAVIGATION SYSTEM

Item	Description	Wgt(Lbs)	Vol(cu. in.)	Power Watts
1	EARTH/SUN TRACKER Az-El Mount, Tracking Optics, drive motors and angle pickoffs.	40	1200	50

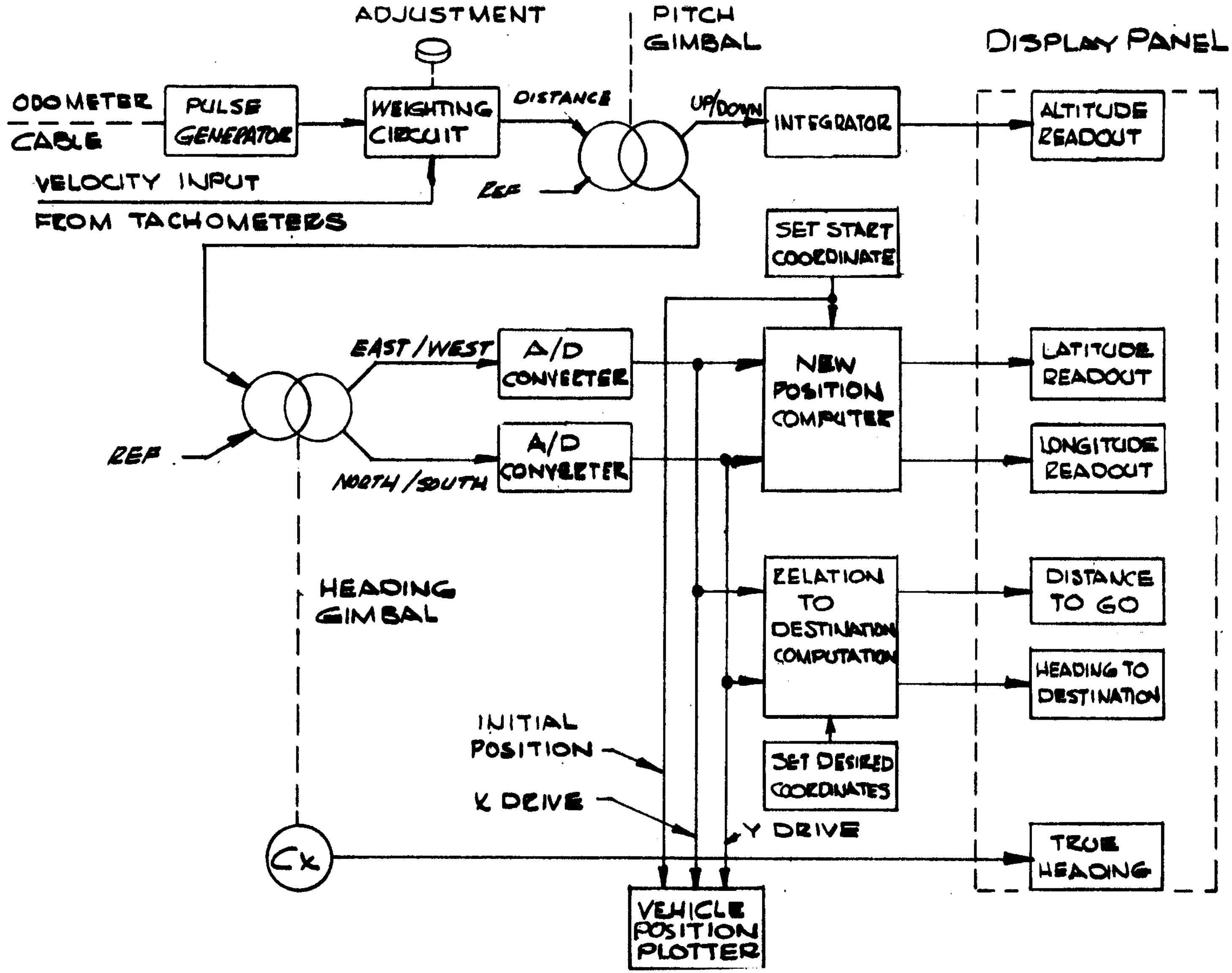

FIGURE 7. BLOCK DIAGRAM OF DEAD RECKONING EQUIPMENT

Item	Description	Wgt(Lbs)	Vol(cu. in)	Power Watts
2	PLATFORM 3 gimbal platform, gyros torques, level sensors, drive electronics	60	2000	170
3	NAVIGATION COMPUTER General purpose digital	32	1400	100
4	DISPLAY PANEL	10	800	100
5	CONTROL PANEL	10	800	100
6	POWER CONDITIONER	10	500	20
7	ODOMETER	5	200	10
8	VEHICLE POSITION PLOTTER	16	710	30
9	DEAD RECKONING COMPUTER	11	280	40
	TOTALS	194	7890	620

The above list of physical characteristics was assembled from reports which discussed characteristics of equipments similar to those described in the Table.

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